Journal of Mosquito Research, 2024, Vol.14, No.6, 276-284
http://emtoscipublisher.com/index.php/jmr

Research Insight Open Access

Long-Term Effects of Climate Change on Mosquito-Related Ecosystem Services

Wenfei Zhang
College of Life Sciences, Hainan Normal University, Haikou, 571158, Hainan, China
Corresponding email: wenfei2007@163.com

Journal of Mosquito Research, 2024, Vol.14, No.6 doi: 10.5376/jmr.2024.14.0026
Received: 02 Sep., 2024
Accepted: 11 Oct., 2024
Published: 03 Nov., 2024

Preferred citation for this article:
Zhang W.F., 2024, Long-term effects of climate change on mosquito-related ecosystem services, Journal of Mosquito Research, 14(6): 276-284 (doi: 10.5376/jmr.2024.14.0026)

Abstract Climate change has profound effects on mosquito-related ecosystem services by altering temperature, humidity, and precipitation patterns. This study examines the long-term impacts of climate change on mosquito habitats, population dynamics, and ecosystem services, such as pollination, food web stability, and nutrient cycling. Research highlights that climate change not only extends mosquito breeding seasons but also modifies population composition and ecological interactions, enhancing their adaptability to new environmental conditions. However, these changes also result in negative impacts, such as population imbalances that disrupt ecosystem stability and biodiversity. The research synthesizes case studies, analyzing how mosquito-driven ecosystem services dynamically evolve in different regions under climate change, while underscoring the importance of ecosystem health and sustainable management.

Keywords Climate change; Mosquito-driven ecosystem services; Habitat distribution; Nutrient cycling; Food web stability

1 Introduction

Mosquitoes, often perceived solely as pests and vectors of diseases, play significant roles in various ecosystem services. These include pollination, contributions to the food web, and nutrient cycling. For instance, mosquitoes are known to pollinate certain plants, thereby aiding in the reproduction of these species (Rochlin et al., 2016). Additionally, mosquito larvae serve as a crucial food source for various aquatic organisms, while adult mosquitoes are prey for birds, bats, and other insects, thus maintaining the balance within ecosystems (Wang et al., 2019; Anoopkumar and Aneesh, 2021).

Climate change, characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, has profound impacts on biodiversity. These changes can disrupt the delicate balance of ecosystems, leading to shifts in species distributions, altered community structures, and changes in the timing of biological events (Franklinos et al., 2019; Couper et al., 2021). For mosquitoes, climate change can extend breeding seasons, increase hatch rates, and expand their geographical range, potentially leading to higher mosquito populations and altered interactions within ecosystems (Ramasamy and Surendran, 2012; Andriamifidy et al., 2019).

This study aims to explore the long-term impacts of climate change on mosquito-related ecosystem services, focusing on their roles in pollination, food web dynamics, and nutrient cycling. It seeks to elucidate how these changes may cascade into broader ecological and human health impacts, striving for a comprehensive understanding of the multifaceted contributions of mosquitoes to ecosystems and the potential shifts in their roles driven by climate change.

2 Climate Change and Mosquito Habitats

2.1 Changes in Temperature and Humidity and Their Effects on Mosquito Distribution

Climate change is significantly altering temperature and humidity patterns, which in turn affect mosquito distribution. Increased temperatures can accelerate mosquito life cycles, leading to higher population densities and expanded geographic ranges. For instance, higher temperatures have been shown to increase mosquito pupation rates, although they also make mosquitoes more susceptible to predation (Hunt et al., 2017). Additionally, warmer temperatures can enhance the development of pathogens within mosquitoes, increasing the frequency of blood feeds and thereby the potential for disease transmission (Ramasamy and Surendran, 2012). Changes in humidity also play a crucial role, as mosquitoes require specific moisture levels for breeding and survival. Elevated humidity levels can create more favorable conditions for mosquito proliferation, further expanding their habitats.

2.2 Shifting Geographic Ranges Due to Altered Climate Patterns

As climate patterns shift, mosquitoes are moving into new geographic areas. Species are migrating poleward and to higher elevations to stay within their preferred environmental conditions (Pecl et al., 2017). For example, in the highlands of Africa, rising temperatures are enabling Anopheles mosquitoes, which are vectors for malaria, to inhabit previously unsuitable high-altitude regions (Afrane et al., 2012). This shift in geographic range is not limited to terrestrial ecosystems; aquatic ecosystems are also experiencing changes. Warmer water temperatures and altered water levels are affecting the distribution of mosquito species that rely on aquatic habitats for their larval stages (Woolway et al., 2022). These shifts can lead to novel biotic communities and interactions, potentially increasing the risk of mosquito-borne diseases in new areas.

2.3 Impacts on aquatic ecosystems and larval habitats

Aquatic ecosystems, which serve as crucial larval habitats for mosquitoes, are being profoundly affected by climate change. Increased water temperatures and altered discharge patterns are changing the physicochemical properties of these habitats, impacting mosquito larval development and survival (Baranov et al., 2020). For instance, higher water temperatures can lead to reduced dissolved oxygen levels, which can affect the growth and mortality rates of mosquito larvae (Gallegos-Sánchez et al., 2022). Additionally, changes in water quality parameters such as pH, turbidity, and nutrient concentrations can influence mosquito presence and abundance (Avramov et al., 2023). The expansion of brackish and saline water bodies due to rising sea levels is also creating new habitats for salinity-tolerant mosquito species, further complicating the dynamics of mosquito-borne disease transmission (Ramasamy and Surendran, 2012).

3 Mosquito-Driven Ecosystem Services

3.1 Pollination: role of mosquitoes in tropical and subtropical ecosystems

Mosquitoes, often recognized primarily as vectors of disease, also play a role in pollination, particularly in tropical and subtropical ecosystems. While their contribution is not as significant as that of bees or butterflies, mosquitoes can aid in the pollination of certain plant species. This role is especially noted in environments where other pollinators are less prevalent, and mosquitoes can help maintain the biodiversity of these ecosystems by supporting the reproductive processes of various plant species (Franklinos et al., 2019; Tsantalidou et al., 2023).

3.2 Contribution to the food web: prey for birds, amphibians, and other species

Mosquitoes are a crucial component of the food web, serving as prey for a variety of species, including birds, amphibians, and other insects. Their larvae are particularly important in aquatic ecosystems, providing a food source for fish and other aquatic organisms. This role supports the survival and reproduction of these predator species, thereby maintaining ecological balance and biodiversity (Andriamifidy et al., 2019; Wang et al., 2019). The presence of mosquitoes can influence the population dynamics of their predators, which in turn affects the broader ecosystem structure (Baranov et al., 2020; Anoopkumar and Aneesh, 2021).

3.3 Nutrient cycling: decomposition and nutrient redistribution by mosquito activity

Mosquitoes contribute to nutrient cycling through their life processes. As larvae, they feed on organic matter in water bodies, aiding in decomposition and nutrient redistribution. This activity helps in breaking down organic material, which releases nutrients back into the ecosystem, supporting plant growth and maintaining soil fertility (Kolimenakis et al., 2019; Couper et al., 2021). The decomposition process facilitated by mosquito larvae is essential for nutrient cycling in aquatic environments, promoting the health and productivity of these ecosystems (Weiskopf et al., 2020).

4 Climate-Induced Changes in Mosquito Populations

4.1 Population dynamics under rising temperatures

Rising temperatures due to climate change significantly impact mosquito population dynamics. Studies have shown that temperature fluctuations can accelerate mosquito development rates, affecting survival and reproductive success. For instance, increased temperatures can lead to faster development times and earlier emergence of mosquitoes, as observed in Culex pipiens s.l. (Boerlijst et al., 2022). Additionally, temperature changes can alter the physiological responses of mosquitoes, such as gene expression and microbiome composition, which are crucial for their survival and vector competence (Bellone et al., 2023). These changes suggest that mosquitoes may thrive under warmer conditions, potentially increasing the risk of mosquito-borne diseases.

4.2 Changes in breeding cycles and reproductive success

Climate change influences mosquito breeding cycles and reproductive success by altering environmental conditions such as temperature and rainfall. For example, Aedes albopictus, a vector mosquito, shows changes in population dynamics with varying rainfall patterns, which affect larval carrying capacity and egg diapause (Fukui et al., 2022) (Figure 1). Furthermore, increased eutrophication and temperature fluctuations have been shown to positively impact egg-laying behavior, although salinity can have adverse effects (Boerlijst et al., 2022). These findings indicate that climate-induced changes in environmental conditions can significantly affect mosquito reproductive success and population growth.

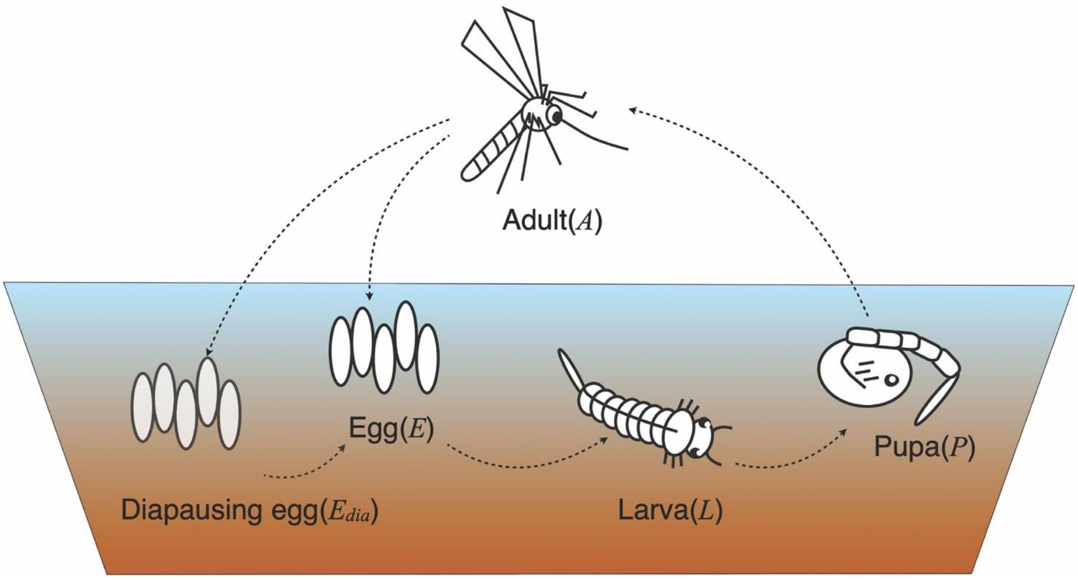

Figure 1 Framework of physiology-based climate-driven mosquito population (PCMP) model for Aedes albopictus (Adopted from Fukui et al., 2022)

4.3 Altered species composition and ecological interactions

Climate change can lead to shifts in species composition and ecological interactions among mosquito populations. As temperatures rise, some mosquito species may adapt more readily than others, leading to changes in community structure. For instance, the potential for thermal adaptation in mosquitoes, such as Aedes aegypti, is influenced by their short generation times and high population growth rates, which may allow them to persist under changing climatic conditions (Couper et al., 2020; 2021). Additionally, climate-driven changes in mosquito physiology and behavior can alter interactions with pathogens and other species, potentially affecting disease transmission dynamics (Caldwell et al., 2021; Bellone et al., 2023). These alterations in species composition and ecological interactions underscore the complexity of predicting mosquito population responses to climate change.

5 Positive and Negative Impacts on Ecosystem Services

5.1 Enhanced pollination in certain regions due to longer seasons

Climate change has led to longer warm seasons in some regions, which can enhance pollination services. Mosquitoes, although primarily known as vectors for diseases, also play a role in pollination. The extended warm periods can increase the activity and lifespan of mosquitoes, thereby potentially enhancing pollination in certain ecosystems. This can be particularly beneficial in regions where other pollinators are declining due to various environmental stresses (Rochlin et al., 2016; Anoopkumar and Aneesh, 2021).

5.2 Disruption in food web stability from population imbalances

The alteration of mosquito populations due to climate change can significantly disrupt food web stability. Increased temperatures and changing precipitation patterns can lead to population imbalances, where mosquito populations may either surge or decline unpredictably. Such imbalances can affect predators that rely on mosquitoes as a food source and can also lead to increased competition among mosquito species, further destabilizing the ecosystem (Ramsfield et al., 2016; Rochlin et al., 2016; Weiskopf et al., 2020). These disruptions can have cascading effects, impacting not only the immediate food web but also broader ecosystem functions and services.

5.3 Loss of services in areas with extreme climate conditions

In regions experiencing extreme climate conditions, such as prolonged droughts or severe flooding, the ecosystem services provided by mosquitoes can be severely diminished. Extreme weather events can lead to habitat loss and reduced mosquito populations, which in turn can affect the species that depend on them. Additionally, the loss of mosquito populations in these areas can disrupt the ecological balance, leading to a decline in biodiversity and the overall health of the ecosystem (Ramsfield et al., 2016; Weiskopf et al., 2020; Anoopkumar and Aneesh, 2021). This loss of services can have significant implications for natural resource management and the sustainability of ecosystem services in affected regions.

6 Case Studies

6.1 Effects on mosquito-mediated pollination in tropical regions

Mosquitoes play a crucial role in pollination within tropical ecosystems, and climate change is expected to significantly impact this service. Rising temperatures and altered precipitation patterns can affect mosquito life cycles and behaviors, potentially disrupting their pollination activities. For instance, higher temperatures can reduce the longevity and fecundity of mosquitoes, which may decrease their effectiveness as pollinators (Agyekum et al., 2021). Additionally, climate change can lead to shifts in mosquito populations, with some species adapting to new thermal conditions while others may decline or migrate, further impacting pollination dynamics (Couper et al., 2021) (Figure 2). These changes could have cascading effects on plant reproduction and biodiversity in tropical regions.

6.2 Impact on aquatic ecosystems in subtropical and temperate areas

Climate change is predicted to have profound effects on aquatic ecosystems in subtropical and temperate regions, where mosquitoes are integral components. Increased water temperatures and altered hydrological cycles can affect mosquito larvae development and survival rates, leading to changes in mosquito population dynamics (Baranov et al., 2020). For example, in Northwest Africa, a shift from temperate to arid conditions is expected to reduce freshwater insect family richness by 37%, which includes mosquito species (Kaczmarek et al., 2021). Furthermore, changes in water temperature and flow patterns can disrupt the ecological balance, affecting not only mosquitoes but also other aquatic organisms and the services they provide (Velayutham et al., 2021). These disruptions can lead to a decline in ecosystem health and resilience, impacting biodiversity and ecosystem services.

6.3 Long-term implications for biodiversity in high-altitude regions

High-altitude regions are particularly vulnerable to climate change, with significant implications for biodiversity, including mosquito species. As temperatures rise, mosquito species that were previously restricted to lower altitudes may expand their range into higher elevations, potentially introducing new diseases and altering local ecosystems (Marques et al., 2021). This shift can lead to increased competition with native species and changes in community structure (Mata-Guel et al., 2023). Additionally, the unique biodiversity of high-altitude regions, which includes specialized and often endemic species, may be at risk due to the introduction of new mosquito species and the associated ecological changes (Weiskopf et al., 2020). Long-term, these changes could result in a loss of biodiversity and the degradation of ecosystem services that are critical for the health and functioning of high-altitude environments.

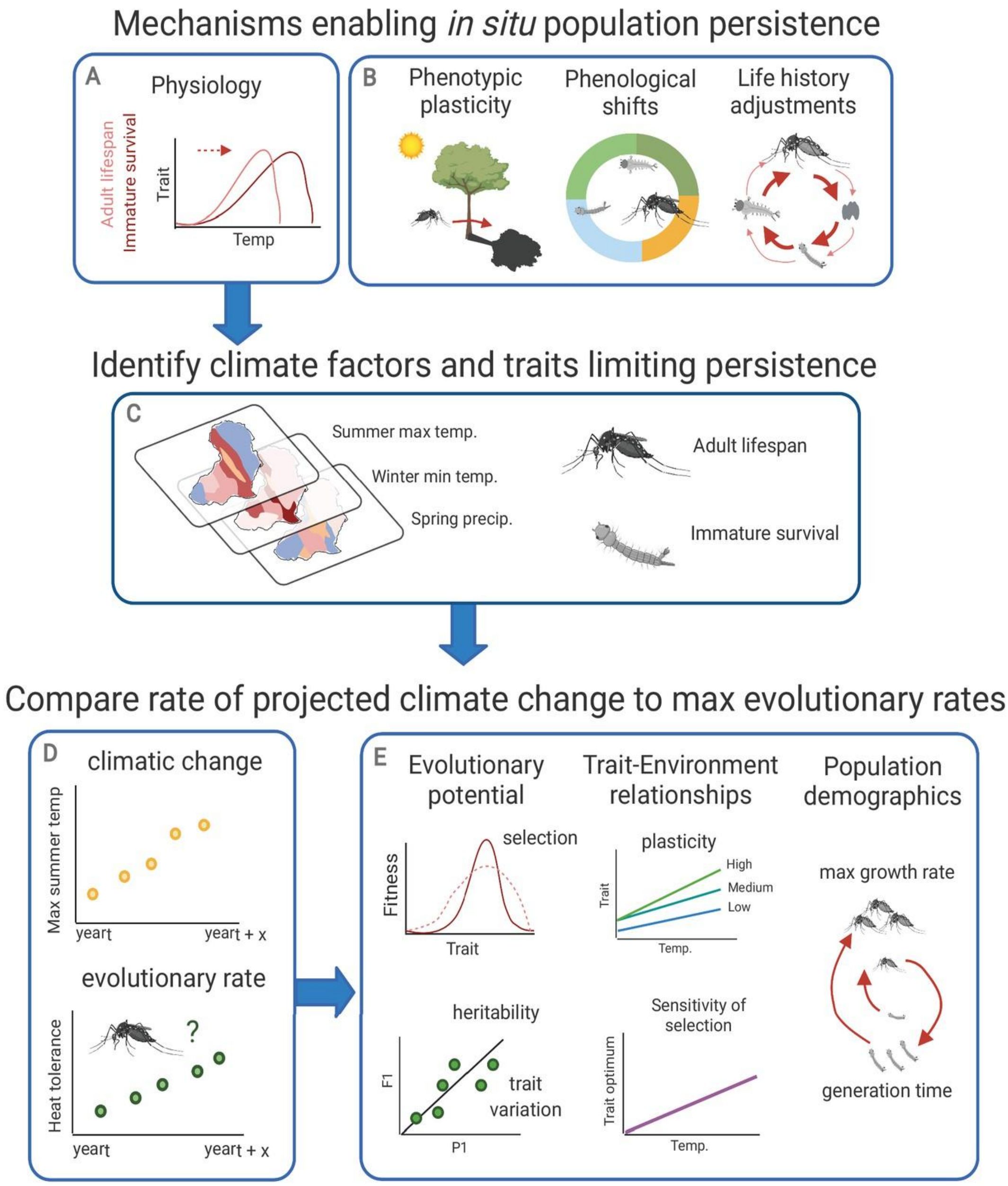

Figure 2 Framework for investigating climate adaptive potential (Adopted from Couper et al., 2021)

Image caption: Several mechanisms may enable in situ population persistence (evolutionary adaptations in physiology, phenotypic plasticity, phenological shifts, and life history adjustments; panels A and B). Investigating the potential for evolutionary climate adaptation requires first identifying the climate factors and traits limiting population persistence (panel C), then comparing the rate of projected climatic change to potential evolutionary rates (panel D). Evolutionary rates can be estimated based on evolutionary potential (strength of selection, and heritability and variation in the trait of interest), population demographic characteristics (maximum growth rate and generation time), and trait-environment relationships (phenotypic plasticity and environmental sensitivity of selection) (panel E). In the strength of selection image (top left, panel E), the dashed and solid lines indicate the population before and after natural selection, respectively. In the heritability panel (bottom left), P1 and F1 denote the parental and offspring generations, respectively (Adopted from Couper et al., 2021)

7 Adaptation and Mitigation Strategies

7.1 Enhancing natural mosquito habitats to support ecosystem services

Enhancing natural mosquito habitats can play a crucial role in supporting ecosystem services. Mosquitoes are integral to various ecological functions, such as serving as food for other wildlife and participating in pollination processes. However, climate change poses significant challenges to these habitats, necessitating adaptive strategies. For instance, restoring and protecting wetlands can enhance the resilience of mosquito populations to climate change, thereby maintaining their ecological roles (Morecroft et al., 2019). Additionally, integrating evolutionary rescue models can help predict and manage mosquito thermal adaptation, ensuring that these species continue to thrive in changing climates (Couper et al., 2020; 2021).

7.2 Balancing disease management with ecosystem conservation

Balancing disease management with ecosystem conservation is essential to mitigate the adverse effects of mosquito-borne diseases while preserving ecological integrity. Traditional mosquito control methods, such as chemical pesticides, often have detrimental impacts on ecosystems and human health. Therefore, adopting ecological mosquito control strategies, such as habitat modification and biological control, can reduce disease transmission without harming the environment (Anoopkumar and Aneesh, 2021). Moreover, multi-sectoral strategies that address urban heat islands and other climate-related factors can simultaneously manage mosquito populations and enhance urban health resilience (Ligsay et al., 2021).

7.3 Integrating climate resilience into ecosystem service frameworks

Integrating climate resilience into ecosystem service frameworks involves considering the impacts of climate change on mosquito-related ecosystem services and developing adaptive management strategies. Predictive models that incorporate climate and land-use changes can improve our understanding of future mosquito distribution and abundance, aiding in the development of effective mitigation strategies (Madzokere et al., 2020). Additionally, ecosystem-based adaptation measures, such as restoring natural habitats and enhancing biodiversity, can increase the resilience of ecosystems to climate change, thereby sustaining the services they provide (Morecroft et al., 2019; Weiskopf et al., 2020). Implementing these strategies requires a holistic approach that considers the interconnectedness of climate, ecosystems, and human health (Franklinos et al., 2019; Giesen et al., 2020).

8 Emerging Research Technologies

8.1 Advances in climate modeling for predicting mosquito population shifts

Recent advancements in climate modeling have significantly enhanced our ability to predict shifts in mosquito populations due to climate change. These models incorporate various environmental variables and high-resolution data to forecast the potential distribution and dynamics of mosquito species under different climate scenarios. For instance, ecological niche models have been used to predict the future distribution of Culex pipiens pallens and Culex pipiens quinquefasciatus in China, showing potential northward shifts in their ranges under climate change scenarios (Liu et al., 2020). Additionally, integrated statistical and mechanistic species distribution models (SDMs) have been developed to improve predictions of mosquito-vector abundance, diversity, and distributions by incorporating both biotic and environmental variables (Madzokere et al., 2020). These models are crucial for identifying high-risk areas and guiding public health interventions.

8.2 Genomic tools to study mosquito adaptations to climate change

Genomic tools have become invaluable in studying how mosquitoes adapt to changing climatic conditions. Genomic sequencing and molecular detection assays allow researchers to detect signatures of infectious pathogens and understand the microbial communities within mosquito vectors (Yeh et al., 2020). These tools help uncover the mechanistic relationships between climate variability and pathogen transmission. For example, evolutionary rescue models have been applied to investigate the potential for climate adaptation in mosquitoes, focusing on thermal adaptation and the role of phenotypic plasticity (Couper et al., 2021). Such genomic studies are essential for predicting how mosquito populations might evolve in response to climate change and for developing strategies to mitigate the spread of mosquito-borne diseases.

8.3 Remote sensing and gis in habitat and population analysis

Remote sensing and Geographic Information Systems (GIS) have revolutionized the analysis of mosquito habitats and populations. These technologies enable the monitoring of environmental conditions and changes that affect mosquito populations. For instance, remote sensing data, such as the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST), have been used to predict mosquito population sizes and their spatial and temporal patterns (Kofidou et al., 2021). Additionally, remote sensing and system dynamics modeling techniques have been recommended to better understand and mitigate mosquito-borne diseases in the context of global change processes (Franklinos et al., 2019). These tools provide critical insights into the environmental factors driving mosquito population dynamics and help in the development of targeted control measures.

9 Conclusion and Future Perspectives

The long-term effects of climate change on mosquito-related ecosystem services are intricate and multifaceted. Mosquito populations and their distribution are heavily influenced by climate change, compounded by anthropogenic factors such as urbanization and chemical usage. For example, the decrease in residual environmental DDT concentrations and increased urban development have contributed to a tenfold rise in mosquito populations in North America over the past five decades, independent of temperature changes. Moreover, the short generation times and high reproductive rates of mosquitoes enhance their capacity for thermal adaptation, allowing them to adjust to shifting climatic conditions. However, the overall impact of climate change on mosquito-borne diseases remains uncertain, as these effects intersect with other global change processes, creating complex dynamics that are not yet fully understood.

Future research should address several critical areas to better understand and manage the impacts of climate change on mosquito-related ecosystem services. First, it is essential to adopt a multifactorial approach by integrating climate change with other drivers such as land-use changes, socioeconomic developments, and chemical usage, all of which can modulate disease risks. Second, advanced modeling techniques, including remote sensing and system dynamics modeling, should be utilized to improve predictive accuracy and guide effective mitigation strategies. Third, research should focus on phenotypic and genotypic variations within mosquito populations to clarify their adaptive potential in changing environments. Finally, given the expansion of saline and brackish water bodies due to rising sea levels, greater emphasis should be placed on studying mosquito population dynamics and salinity adaptation in coastal zones, which are increasingly vulnerable to climate change.

Sustainable practices are vital to preserving mosquito-driven ecosystem services amidst the challenges posed by climate change. Traditional mosquito control strategies, such as the extensive use of chemical pesticides, are limited by the emergence of insecticide resistance and their detrimental effects on ecosystems. Therefore, ecological-based mosquito control methods, including habitat modification and biological control, should be prioritized to ensure long-term sustainability. Additionally, monitoring mosquito populations in protected areas can provide valuable insights into their natural responses to climate change, devoid of anthropogenic disturbances. Such efforts will not only support biodiversity conservation but also contribute to the development of adaptive management strategies to mitigate the impacts of climate change on mosquito populations and the ecosystem services they provide.

Acknowledgments

Thanks to Ms Lisa Wu, for the inspiration and support during academic discussions and daily exchanges. Your encouragement kept me motivated during challenging times and helped me complete this research.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Afrane Y., Githeko A., and Yan G., 2012, The ecology of Anopheles mosquitoes under climate change: case studies from the effects of deforestation in East African highlands, Annals of the New York Academy of Sciences, 3: 1249.
https://doi.org/10.1111/j.1749-6632.2011.06432.x

Agyekum T., Botwe P., Arko-Mensah J., Issah I., Acquah A., Hogarh J., Dwomoh D., Robins T., and Fobil J., 2021, A Systematic review of the effects of temperature on anopheles mosquito development and survival: implications for malaria control in a future warmer climate, International Journal of Environmental Research and Public Health, 2(4): 18.
https://doi.org/10.3390/ijerph18147255

Andriamifidy R., Tjaden N., Beierkuhnlein C., and Thomas S., 2019, Do we know how mosquito disease vectors will respond to climate change?, Emerging Topics in life Sciences, 3(2): 115-132.
https://doi.org/10.1042/ETLS20180125

Anoopkumar A., and Aneesh E., 2021, A critical assessment of mosquito control and the influence of climate change on mosquito-borne disease epidemics, Environment Development and Sustainability, 24(6): 8900-8929.
https://doi.org/10.1007/s10668-021-01792-4

Avramov M., Thaivalappil A., Ludwig A., Miner L., Cullingham C., Waddell L., and Lapen D., 2023, Relationships between water quality and mosquito presence and abundance: a systematic review and meta-analysis, Journal of Medical Entomology, 61(1): 1-33.
https://doi.org/10.1093/jme/tjad139

Baranov V., Jourdan J., Pilotto F., Wagner R., and Haase P., 2020, Complex and nonlinear climate-driven changes in freshwater insect communities over 42 years, Conservation Biology, 34(5): 1241-1251.
https://doi.org/10.1111/cobi.13477

Bellone R., Lechat P., Mousson L., Gilbart V., Piorkowski G., Bohers C., Merits A., Kornobis E., Reveillaud J., Paupy C., Vazeille M., Martinet J., Madec Y., De Lamballerie X., Dauga C., and Failloux A., 2023, Climate change and vector-borne diseases: a multi-omics approach of temperature-induced changes in the mosquito, Journal of Travel Medicine, 30(4): taad062.
https://doi.org/10.1093/jtm/taad062

Boerlijst S., Johnston E., Ummels A., Krol L., Boelee E., Van Bodegom P., and Schrama M., 2022, Biting the hand that feeds: Anthropogenic drivers interactively make mosquitoes thrive, The Science of the Total Environment, 858: 159716.
https://doi.org/10.2139/ssrn.4159446

Caldwell J., LaBeaud A., Lambin E., Stewart-Ibarra A., Ndenga B., Mutuku F., Krystosik A., Ayala E., Anyamba A., Borbor-Cordova M., Damoah R., Grossi-Soyster E., Heras F., Ngugi H., Ryan S., Shah M., Sippy R., and Mordecai E., 2021, Climate predicts geographic and temporal variation in mosquito-borne disease dynamics on two continents, Nature Communications, 12(1): 1233.
https://doi.org/10.1038/s41467-021-21496-7

Couper L., Farner J., Caldwell J., Childs M., Harris M., Kirk D., Nova N., Shocket M., Skinner E., Uricchio L., Expósito-Alonso M., and Mordecai E., 2021, How will mosquitoes adapt to climate warming?, eLife, 10: e69630.
https://doi.org/10.7554/eLife.69630

Couper L., Farner J., Caldwell J., Childs M., Harris M., Kirk D., Nova N., Shocket M., Skinner E., Uricchio L., Expósito-Alonso M., and Mordecai E., 2020, How will mosquitoes adapt to climate change?, 10: e69630.
https://doi.org/10.22541/au.160589900.06282166/v1

Franklinos L., Jones K., Redding D., and Abubakar I., 2019, The effect of global change on mosquito-borne disease, The Lancet Infectious Diseases, 19(9): e302-e312.
https://doi.org/10.1016/S1473-3099(19)30161-6

Fukui S., Kuwano Y., Ueno K., Atsumi K., and Ohta S., 2022, Modeling the effect of rainfall changes to predict population dynamics of the Asian tiger mosquito Aedes albopictus under future climate conditions, PLoS One, 17(5): e0268211.
https://doi.org/10.1371/journal.pone.0268211

Gallegos-Sánchez S., Domínguez E., Encalada A., and Ríos-Touma B., 2022, Effects of experimental warming on two tropical Andean aquatic insects, PLoS One, 17(7): e0271256.
https://doi.org/10.1371/journal.pone.0271256

Giesen C., Roche J., Redondo-Bravo L., Ruiz-Huerta C., Gómez-Barroso D., Benito A., and Herrador Z., 2020, The impact of climate change on mosquito-borne diseases in Africa, Pathogens and Global Health, 114: 287-301.
https://doi.org/10.1080/20477724.2020.1783865

Hunt S., Galatowitsch M., and McIntosh A., 2017., Interactive effects of land use temperature and predators determine native and invasive mosquito distributions, Freshwater Biology 62: 1564-1577.
https://doi.org/10.1111/FWB.12967

Kaczmarek N., Schäfer R., and Berger E., 2021, Environmental change threatens freshwater insect communities in northwest Africa: a meta-analysis, Frontiers in Environmental Science, 9: 671715.
https://doi.org/10.3389/fenvs.2021.671715

Kofidou M., De Courcy Williams M., Nearchou A., Veletza S., Gemitzi A., and Karakasiliotis I., 2021, Applying remotely sensed environmental information to model mosquito populations, Sustainability, 13(14): 7655.
https://doi.org/10.3390/SU13147655

Kolimenakis A., Bithas K., Latinopoulos D., and Richardson C., 2019, On lifestyle trends health and mosquitoes: Formulating welfare levels for control of the Asian tiger mosquito in Greece, PLoS Neglected Tropical Diseases, 13(6): e0007467.
https://doi.org/10.1371/journal.pntd.0007467

Ligsay A., Telle O., and Paul R., 2021, Challenges to mitigating the urban health burden of mosquito-borne diseases in the face of climate change, International Journal of Environmental Research and Public Health, 18(9): 5035.
https://doi.org/10.3390/ijerph18095035

Liu B., Gao X., Zheng K., Jiao Z., Xiao J., and Wang H., 2020, The potential distribution and dynamics of important vectors Culex pipiens pallens and Culex pipiens quinquefasciatus in China under climate change scenarios: An ecological niche modelling approach, Pest Management Science, 76(9): 3096-3107.
https://doi.org/10.1002/ps.5861

Madzokere E., Hallgren W., Sahin O., Webster J., Webb C., Mackey B., and Herrero L., 2020, Integrating statistical and mechanistic approaches with biotic and environmental variables improves model predictions of the impact of climate and land-use changes on future mosquito-vector abundance diversity and distributions in Australia, Parasites and Vectors, 13: 1-13.
https://doi.org/10.1186/s13071-020-04360-3

Marques R., Krüger R., Cunha S., Silveira A., Alves D., Rodrigues G., Peterson A., and Jiménez-García D., 2021, Climate change impacts on Anopheles (K.) cruzii in urban areas of Atlantic Forest of Brazil: challenges for malaria diseases, Acta tropica, 224: 106123.
https://doi.org/10.1016/j.actatropica.2021.106123

Mata-Guel E., Soh M., Butler C., Morris R., Razgour O., and Peh K., 2023, Impacts of anthropogenic climate change on tropical montane forests: an appraisal of the evidence, Biological Reviews, 98(4): 1200-1224.
https://doi.org/10.1111/brv.12950

Morecroft M., Duffield S., Harley M., Pearce-Higgins J., Stevens N., Watts O., and Whitaker J., 2019, Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems, Science, 366(6471): eaaw9256.
https://doi.org/10.1126/science.aaw9256

Pecl G., Araújo M., Bell J., Blanchard J., Bonebrake T., Chen I., Clark T., Colwell R., Danielsen F., Evengård B., Falconi L., Ferrier S., Frusher S., Garcia R., Griffis R., Hobday A., Janion - Scheepers C., Jarzyna M., Jennings S., Lenoir J., Linnetved H., Martin V., McCormack P., McDonald J., Mitchell N., Mustonen T., Pandolfi J., Pettorelli N., Popova E., Robinson S., Scheffers B., Shaw J., Sorte C., Strugnell J., Sunday J., Tuanmu M., Vergés A., Villanueva C., Wernberg T., Wapstra E., and Williams S., 2017, Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being, Science, 355(6332): eaai9214.
https://doi.org/10.1126/science.aai9214

Ramasamy R., and Surendran S., 2012, Global climate change and its potential impact on disease transmission by salinity-tolerant mosquito vectors in coastal zones, Frontiers in Physiology, 3: 198.
https://doi.org/10.3389/fphys.2012.00198

Ramsfield T., Bentz B., Faccoli M., Jactel H., and Brockerhoff E., 2016, Forest health in a changing world: Effects of globalization and climate change on forest insect and pathogen impacts, Forestry, 89: 245-252.
https://doi.org/10.1093/FORESTRY/CPW018

Rochlin I., Faraji A., Ninivaggi D., Barker C., and Kilpatrick A., 2016, Anthropogenic impacts on mosquito populations in North America over the past century, Nature Communications, 7(1): 13604.
https://doi.org/10.1038/ncomms13604

Tsantalidou A., Arvanitakis G., Georgoulias A., Akritidis D., Zanis P., Fornasiero D., Wohlgemuth D., and Kontoes C., 2023, A data driven approach for analyzing the effect of climate change on mosquito abundance in Europe, Remote. Sens., 15: 5649.
https://doi.org/10.3390/rs15245649

Velayutham S., Silva D., Roque F., Ferreira J., and Heino J., 2021, Predicting climate effects on aquatic true bugs in a tropical biodiversity hotspot, Journal of Insect Conservation, 25: 229-241.
https://doi.org/10.1007/s10841-021-00298-8

Wang Y., Yim S., Yang Y., and Morin C., 2019, The effect of urbanization and climate change on the mosquito population in the pearl river delta region of China, International Journal of Biometeorology, 64: 501-512.
https://doi.org/10.1007/s00484-019-01837-4

Weiskopf S., Rubenstein M., Crozier L., Gaichas S., Griffis R., Halofsky J., Hyde K., Morelli T., Morisette J., Muñoz R., Pershing A., Peterson D., Poudel R., Staudinger M., Sutton-Grier A., Thompson L., Vose J., Weltzin J., and Whyte K., 2020, Climate change effects on biodiversity ecosystem ecosystem services and natural resource management in the United States, The Science of the Total Environment, 733: 137782.
https://doi.org/10.1016/j.scitotenv.2020.137782

Woolway R., Sharma S., and Smol J., 2022, Lakes in hot water: the impacts of a changing climate on aquatic ecosystems, Bioscience, 72: 1050-1061.
https://doi.org/10.1093/biosci/biac052

Yeh K., Fair J., Smith W., Torres T., Lucas J., Monagin C., Winegar R., and Fletcher J., 2020, Assessing climate change impact on ecosystems and infectious disease: important roles for genomic sequencing and a one health perspective, Tropical Medicine and Infectious Disease, 5(2): 90.
https://doi.org/10.3390/tropicalmed5020090